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(54) Title: **AN OPHTHALMIC LENS**

(57) Abstract: An ophthalmic lens comprising a diffractive part and a method for designing such a lens. According to the invention the ophthalmic lens further comprises a refractive part comprising at least one surface, which is configured to compensate a passing wavefront at least partly for at least one type of monochromatic aberration introduced by at least one of the optical parts of the eye. Said diffractive part is capable of compensating a passing wavefront at least partly for chromatic aberration introduced by at least one of the optical parts of the eye. Furthermore said refractive and diffractive parts together contribute to a required power of the lens.

An ophthalmic lens

## TECHNICAL FIELD OF THE INVENTION

5 The present invention relates to an ophthalmic lens comprising a diffractive part.

Furthermore it relates to a method for designing said ophthalmic lenses.

## BACKGROUND OF THE INVENTION

10

A wavefront passing the eye will be influenced by the optical parts of the eye such that for example chromatic aberration is provided to the wavefront. The reason is that the refractive indices of the materials in the optical parts of the eye differ for different wavelengths. Thus light having different wavelengths will be refracted a different  
15 amount and they will fall on the retina at different places, i.e. different colors can not be focused to the same point. This is called chromatic aberration.

Recently there has been much interest in the correction of the monochromatic aberrations of the eye. It has been revealed that when all monochromatic aberrations  
20 are corrected in the human visual system, it serves to unmask the chromatic aberration of the eye. Therefore, in order to optimize the optical quality of the eye, a combination of monochromatic and chromatic aberrations needs to be corrected. A diffractive pattern could be configured to provide a passing wavefront with chromatic aberration of the opposite sign as chromatic aberration from the eye. Thus a  
25 diffractive pattern can be used to correct for chromatic aberration introduced to a wavefront from the optical parts of the eye. Some background theory of chromatic aberration can be found in, for example Chapter 17 in "Optics of the Human Eye" written by David A. Atchison and George Smith. A theoretical background of the diffractive pattern could be found in the article "Practical design of a bifocal hologram  
30 contact lens or intraocular lens", Allen L. Cohen, Applied Optics 31(19)(1992). Ophthalmic lenses, which on at least one surface comprises a diffractive pattern for correcting for chromatic aberration are known from for example US 5,895,422, US 5,117,306 and US 5895422. These lenses do, however not, compensate for other aberrations provided by the eye surfaces. In SE 0000614-4, aspheric lenses are

designed to compensate for spherical aberration. In some applications these lenses will provide the eye with an increase in chromatic aberration. It is therefore a need of an ophthalmic lens for correcting refractive errors that also can correct for monochromatic and chromatic aberrations.

5

## DESCRIPTION OF THE INVENTION

An object of the present invention is to improve the visual quality for a patient.

- 10 A further object of the present invention is to provide an ophthalmic lens, which corrects for chromatic aberration and at least one type of monochromatic aberration.

A further object of the present invention is to provide an ophthalmic lens, which corrects for both chromatic and spherical aberration.

15

Still a further object of the invention is to correct for spherical aberration as expressed by the 11<sup>th</sup> normalized Zernike term.

- 20 A yet further object is to provide an aspheric lens capable of correcting for spherical aberration having a diffractive part adding refractive power to the lens and providing compensation for chromatic aberration introduced by the optical surfaces of the eye and by the aspheric lens surface. In this text the term aspheric will refer to rotationally symmetric, asymmetric and/or irregular surfaces, i.e. all surfaces differing from a sphere.

25

- These objects are achieved by an ophthalmic lens as initially described in "technical field of invention", which according to the invention further comprises a refractive part comprising at least one surface, which is configured to compensate a passing wavefront at least partly for at least one type of monochromatic aberration introduced by at least one of the optical parts of the eye. The diffractive part is according to the invention capable of compensating a passing wavefront at least partly for chromatic aberration introduced by at least one of the optical parts of the eye. Said refractive and diffractive parts together contribute to a required power of the lens. In this text "the optical parts of the eye" refer to the parts of the eye that contribute to the refraction of
- 30

incoming light. The cornea of the eye and the natural or an implanted lens are optical parts of the eye. But also inhomogeneities, e.g. in the vitreous are considered as the optical parts of the eye. An optical element that combines both diffractive and refractive optics is called a hybrid element. The monochromatic aberration could be  
 5 for example astigmatism, coma, spherical aberration, trifoil, tetrafoil or higher aberration terms.

Hereby an ophthalmic lens is achieved that is capable of compensating for at least one type of monochromatic aberration and for chromatic aberration introduced by the  
 10 optical parts of the eye to a passing wavefront.

Preferably the diffractive part also is capable of compensating a passing wavefront at least partly for chromatic aberration introduced by the refractive part of the lens.

15 In one embodiment of the invention the monochromatic aberration corrected for is spherical aberration.

The longitudinal chromatic aberration of the eye is very well understood and has been shown to have very similar values from subject to subject (Thibos et. al., "The  
 20 chromatic eye: a new reduced eye model of ocular chromatic aberration in humans", Applied Optic, 31; 3594-3600, (1992)). It has also been shown to be stable with age (Mordi et. al., "Influence of age on chromatic aberration of the human eye", Amer. J. Optom. Physiol. Opt., 62, 864-869 (1985)). Hereby an ophthalmic lens to correct for the average chromatic aberration of the eye could be designed.

25 Diffractive surfaces can be characterised by their so called phase functions. This phase function describes the additional phase that is added to a ray when it passes the diffractive surface. This additional phase is dependent on the radius of the lens where the ray strikes the surface. For radially symmetric diffractive surfaces this function  
 30 can be described using Equation 1.

$$\phi(r) = \frac{2\pi}{\lambda} (DFO + DF1r + DF2r^2 + DF3r^3 + DF4r^4 + \dots) \quad (1)$$

Where  $r$  is the radial coordinate,  $\lambda$  the wavelength and  $DF0$ ,  $DF1$  etc. are the coefficients of the polynomial.

The diffractive part of the lens can also introduce some spherical aberration to a passing wavefront. Preferably, according to the present invention, the refractive part is made capable to compensate a passing wavefront for the spherical aberration introduced by the diffractive part of the lens. Hereby, the spherical aberration could be reduced to a minimum after the wavefront has passed the optical parts of the eye and said lens.

10

To compensate for the spherical aberration, an aspherical surface, with a lateral height described by Equation 2, could be introduced to the refractive part of the lens. An aspheric surface can be configured to counteract the spherical aberration introduced by the optical parts of the eye and by the diffractive part of the lens. All the optical parts of the eye do not necessarily have to be considered. In one embodiment it is sufficient to measure the spherical aberration introduced by the cornea of the eye and compensate for only the spherical aberration provided by the cornea and optionally also for the spherical aberration introduced by the diffractive part of the lens. For example Zernike terms could be used to describe the optical surfaces of the eye and thus also be used to configure the aspheric surface of the lens, which is adapted to compensate for the spherical aberration. Table 1 shows the first 15 normalized Zernike terms and the aberrations each term signifies. The spherical aberration is the 11<sup>th</sup> normalized Zernike term. The designing of a lens that is adapted to compensate for aberrations as expressed in Zernike terms is explained in further detail in the Swedish patent application SE 0000614-4 to which is given reference.

25

$$z = \frac{\left(\frac{1}{R}\right) * r^2}{1 + \sqrt{1 - \left(\frac{1}{R}\right)^2 (cc + 1)r^2}} + AD r^4 + AE r^6 \quad (2)$$

Where  $R$  is the radial coordinate of the lens,  $cc$  is the conic constant, and  $AD$  and  $AE$  are coefficients of the polynomial extension.

30

i	$Z_i(\rho, \theta)$ (normalized format)	form associated with normalized polynomial
1	1	Piston
2	$2\rho \cos \theta$	Tilt x
3	$2\rho \sin \theta$	Tilt y
4	$\sqrt{3}(2\rho^2 - 1)$	Defocus
5	$\sqrt{6}(\rho^2 \sin 2\theta)$	Astigmatism 1 <sup>st</sup> order (45°)
6	$\sqrt{6}(\rho^2 \cos 2\theta)$	Astigmatism 1 <sup>st</sup> order (0°)
7	$\sqrt{8}(3\rho^3 - 2\rho) \sin \theta$	Coma y
8	$\sqrt{8}(3\rho^3 - 2\rho) \cos \theta$	Coma x
9	$\sqrt{8}(\rho^3 \sin 3\theta)$	Trifoil 30°
10	$\sqrt{8}(\rho^3 \cos 3\theta)$	Trifoil 0°
11	$\sqrt{5}(6\rho^4 - 6\rho^2 + 1)$	spherical aberration
12	$\sqrt{10}(4\rho^4 - 3\rho^2) \cos 2\theta$	Astigmatism 2 <sup>nd</sup> order (0°)
13	$\sqrt{10}(4\rho^4 - 3\rho^2) \sin 2\theta$	Astigmatism 2 <sup>nd</sup> order (45°)
14	$\sqrt{10}(\rho^4 \cos 4\theta)$	Tetrafoil 0°
15	$\sqrt{10}(\rho^4 \sin 4\theta)$	Tetrafoil 22.5°

Table 1

- 5 The spherical aberration of the lens is influenced by the shape factor of the lens. The spherical aberration of a spherical refractive lens can be minimized by a convex-plano lens (Atchison D.A., "Optical Design of Intraocular lenses. I: On-axis Performance", Optometry and Vision Science, 66 (8), 492-506, (1989)). In the present invention, the amount of correction of spherical aberration depends on the shape factor of the lens. It
- 10 is also possible to use a diffractive pattern that is able to correct for spherical aberration as well as for chromatic aberration. This can be done by modifying the

higher orders of the phase function of the diffractive profile (lower orders, or terms on  $r^2$  (Equation 1), describe the paraxial properties of the lens).

- Other types of monochromatic aberrations can also be corrected for by aspheric refractive surfaces. The shape of the surface becomes more complex the higher the order of the aberration that is corrected. To compensate for a general aberration with an aspherical surface, the lateral height could be described by Equation 3, though also other descriptions are possible.

$$z = \sum_{i=1}^n z_i$$

$$z_i = (asi)x^j y^k$$

$$i = \frac{1}{2}[(j+k)^2 + j + 3k]$$

- Where  $asi$  are the coefficients of the polynomial.

- Preferably the ophthalmic lens together with the eye provides a polychromatic image quality, which when expressed as MTF(50) (Modulation Transfer Function at 50 cycles per millimeter) performs at least about 40% higher than an aspheric lens compensating for the same spherical aberration as the inventive lens but without compensating for the chromatic aberration. A high value of the polychromatic image quality indicates that the amount of chromatic aberration is small and also that the amount of monochromatic aberrations is small.

- The lens can correct for the spherical aberrations and the chromatic aberrations as defined in a model eye. Spherical aberration of the eye can run between zero and 1.5 diopter, while chromatic aberration typically runs up to 2.5 diopters ("Optics of the Human Eye" written by David A. Atchison and George Smith).

- Suitably, the diffractive part is a diffractive surface profile. Such a diffractive surface profile consists of a number of concentric rings. The distances between the rings are decreasing out from the center of the lens. The area between two rings is called a zone. The width of the first zone is a constant that defines the widths of all the other

zones. For more background techniques see the article by Allen L. Cohen referred to on page 1 in this application.

5 In one embodiment, the profile height is equal to one design wavelength. 550 nm is often used as the design wavelength since this is the wavelength for which the retina has its maximum sensitivity. When the profile height is equal to one design wavelength the lens will have its maximum effect in its first order. The profile height is, in another embodiment equal to two design wavelengths and then the lens will have its maximum effect in its second order. See e.g. the aforementioned article by  
10 Allen L. Cohen and the US patents US 5,895,422, US 5,117,306, US 5,895,422. The profile height could be any integer number of the design wavelengths.

In one embodiment of the invention the anterior surface of the lens is an aspheric surface, on which a diffractive profile is superimposed. In another embodiment of the  
15 invention the anterior surface of the lens is an aspheric surface and the posterior surface of the lens is flat and has a diffractive profile. Also other combinations are possible. For example a diffractive profile could be provided on both the anterior and the posterior surface. Both the anterior and posterior surfaces could also be aspheric. The skilled person can readily identify alternative lens configurations which will be  
20 suitable to design the inventive chromatic and monochromatic aberration reducing lenses.

The objects are also achieved by a method as initially described comprising combining a refractive part and a diffractive part of the lens such that they together  
25 compensate a passing wavefront at least partly for at least one type of monochromatic aberration and for chromatic aberration introduced by at least one of the optical parts of the eye, while dimensioning said refractive and diffractive parts to provide the lens with a required power.

30 In one embodiment the method further comprises measuring at least one type of monochromatic aberration provided to a wavefront from at least one of the optical parts of an eye and combining the refractive and diffractive parts of the lens such that they compensate at least partly for the measured monochromatic aberration.



In one embodiment of the invention the measured monochromatic aberration is spherical aberration.

The spherical aberration of the whole eye could be measured using a wavefront  
5 sensor. If only the cornea is considered well-known topographical measurement  
methods could be used. Such topographical methods are disclosed in for example  
"Corneal wave aberration from videokeratography: accuracy and limitations of the  
procedure", Antonio Guirao and Pablo Artal, J. Opt. Soc. Am. Opt. Image Sci. Vis.,  
Jun, 17(6), 955-965, (2000). A wavefront sensor is described in US Patent No.  
10 5,777,719 (Williams et.al.).

Suitably, the method further comprises measuring the chromatic aberration provided  
to a wavefront from at least one of the optical parts of the eye and combining the  
refractive and diffractive parts of the lens such that they together compensate a  
15 passing wavefront at least partly for the measured chromatic aberration introduced by  
at least one of the optical parts of the eye. The chromatic aberration of the eye could  
be measured by using vernier methods such as those similar to the methods outlined  
in Thibos et.al., "Theory and measurement of ocular chromatic aberration", Vision  
Res., 30, 33-49 (1990) and Marcos et. al, Vision Research, 39, 4309-4323, (1999).  
20 Alternative ways for measuring chromatic aberration are described in a textbook,  
"Optics of the Human Eye" by David A. Atchison and George Smith, published by  
Butterworth-Heinemann, ISBN 0-7506-3775-7.

Preferably, the method further comprises measuring the refractive error of the eye and  
25 dimensioning the refractive and diffractive parts of the lens such that they together  
compensate at least partly for the refractive error of the eye.

With this method of designing an ophthalmic lens the chromatic aberration, the  
spherical aberration and the refractive error of the eye, could all be considered and  
30 compensated for. The lens is designed with one refractive part and one diffractive part  
and they are combined, such that they together compensate a passing wavefront for  
these aberrations introduced by the optical parts of the eye.

The aberration corrections could all be full corrections or partial corrections. Furthermore all the corrections could be based on the aberrations of one or more parts of the eye. The corrections could also be based on either an average value of a certain population or on the measured values of the individual patient or on a combination of  
5 an average value and individual measurements. The certain population can be a group of people in a specific age interval or for example a group of people having had an eye disease or a corneal surgery. For chromatic aberration the values are pretty much the same for all humans so it is possible to take an average value of all kinds of people and correct for this chromatic aberration in the lens. Of course it is possible to do the  
10 same for spherical aberration but in this case it would be preferred to choose a group of people or even measure the spherical aberration for every individual since the spherical aberration will differ more from eye to eye than chromatic aberration.

The ophthalmic lens could be configured to be a phakic or pseudophakic intraocular  
15 lens (IOL), a spectacle lens or a contact lens. In the examples described below the lenses are pseudophakic IOLs. The material used in the example lenses described below is a foldable silicone high refractive index material described in US 5,444,106. Other materials are however also possible for these lenses. For example PMMA (Poly-methylmethacrylate) and hydrogels are suitable materials. The example lenses  
20 have a power of 20D. However, the lenses could be designed to have any other suitable power. Also negative lenses are possible.

A method of designing the ophthalmic lens described above comprises the steps of:

- i) selecting an eye model with a refractive aspheric ophthalmic lens of a  
25 predetermined refractive power and a predetermined amount of at least one monochromatic aberration;
- ii) estimating the power of said eye model at different wavelengths, so as to determine the chromatic aberration of the eye model;
- iii) estimating a correction function of how the power varies with the wavelength  
30 to be an ideal compensation for said chromatic aberration of the eye model;
- iv) finding a linear function of how power varies with the wavelength, which suitably approximates said correction function;

- v) calculating a provisional zone width of a diffractive profile corresponding to this linear function and also calculating the diffractive power of this diffractive profile;
- vi) reducing the refractive power of the refractive ophthalmic lens by the amount of power calculated for the diffractive profile;
- vii) estimating a new correction function of step iii), finding a new linear function of step iv) and calculating a new provisional zone width and a new diffractive power for a new diffractive profile corresponding to this new linear function;
- viii) adjusting the refractive power of the refractive ophthalmic lens such that the total power of a hybrid lens, which comprises both the refractive ophthalmic lens and the diffractive profile and which is adapted to replace the refractive ophthalmic lens in the eye model, equals the predetermined power;
- ix) repeating steps vii) to viii) until a suitable combination of a refractive and a diffractive part of the hybrid ophthalmic lens is found that both provide the eye model with a predetermined power and with a suitable reduction in chromatic aberration.

Suitably this method comprises as a last step measuring the monochromatic aberration of the combination of the eye and the hybrid ophthalmic lens of the method above and correcting the refractive part of the ophthalmic lens according to the measurements such that the monochromatic aberration is reduced sufficiently for the combination of eye and ophthalmic lens.

One example of an eye model that can be used is the eye model of Navarro but other models are also possible. The eye model could also be an individual eye of an individual patient.

In one embodiment the at least one monochromatic aberration of the refractive ophthalmic lens is spherical aberration.

There are different possibilities for the design of the lenses according to the invention. One possibility is to design each lens for each individual. Then the chromatic aberration, the spherical aberration and the refractive error of the eye of the patient are measured and a lens is designed from these values according to the above described

method. Another possibility is to use average values from selected categories of people to design lenses adapted to suit almost all the people belonging to this category. It would then be possible to design lenses having different powers but providing the same reduction of spherical and chromatic aberration to patients within  
5 these groups of people. The groups of people could for example be age groups or groups of people having had specific eye diseases or a group of people having had a corneal surgery. Furthermore it would be possible to provide a kit of lenses having an average value of chromatic aberration and a range of different values of spherical aberration for each power. This could be preferred since the chromatic aberration is  
10 about the same in most human eyes. Hereby it would be necessary to measure the refractive error and the spherical aberration of each individual eye and then choose one lens from this kit of lenses to comply with these measurements.

The following examples are just given as examples and are not intended to be limiting  
15 for the invention in any way.

#### BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 shows a diagram of the relationship between refractive power and wavelength  
20 for an eyemodel and for a diffractive lens.

Fig. 2 shows the Polychromatic Modulation Transfer Function for a hybrid refractive/diffractive lens and two other lenses.

25 Fig. 3 shows the light distribution between the different diffractive orders for a diffractive lens with a profile height of two design wavelengths. Also shown in this plot is the spectral sensitivity of the eye.

Fig. 4 shows the polychromatic Modulation Transfer Function including 1<sup>st</sup> and 3<sup>rd</sup>  
30 order for the lens of Fig. 3 and for two other non-diffractive lenses.

#### DETAILED DESCRIPTION OF EMBODIMENTS

Two examples are described of an intraocular lens (IOL) which corrects for spherical aberration and for chromatic aberration of the pseudophakic eye. Both examples use an aspheric lens surface for correcting the spherical aberration and a diffractive surface profile for correcting the chromatic aberration. The aspheric lens surface  
 5 corrects the spherical aberration of the ocular surfaces, as well as the spherical aberration induced by the diffractive lens profile.

Example 2 has an extended diffractive surface profile. This type of lens is often called a super-zone diffractive lens and such lenses are described in: J.C. Marron et al.,  
 10 "Higher-Order Kinoforms", Computer and optically formed holographic optics, I.Cindrich, et al., editor, Proc. SPIE 1211, 62-66 (1990).

The configuration of the example IOLs is fully described below, based on an eyemodel taken from the literature (Navarro et al, "Accommodation dependent model  
 15 of the human eye with aspherics." JOSA A , 2(8), 1273-1281, (1985)) and based on the data of a silicone material. The optical evaluation is done by ray tracing using the OSLO optical design software (Lambda Research Corporation, Littleton, MA, USA).

### Example 1

20

#### *Background theory:*

Both the cornea and the refractive intraocular lens (IOL) have a positive chromatic aberration, which means that the focal length increases with longer wavelength. A diffractive profile has a negative chromatic aberration. The profile consists of a  
 25 number of rings (zones). For a diffractive lens working in the 1<sup>st</sup> diffraction order, the power of lens can be defined by:

$$P = \frac{2 * \lambda}{w^2}$$

Where P is the lens power,  $\lambda$  is the design wavelength (m) and w is the Half-width (radius) of the first zone.

30

The chromatic aberration (CA) can be described as:

$$CA = -\frac{\partial P}{\partial \lambda} = -\frac{2}{w^2}$$

The diffractive lens power is linearly related to the wavelength. The relation between refractive lens power and wavelength, in refractive systems, is generally not linear.

This is shown in Figure 1 where the relation between refractive power and wavelength for an eyemodel and for a diffractive lens is illustrated. The eyemodel has a non-linear relationship and the diffractive lens has a linear relationship. A curve, representative for an ideal correction is also shown. Therefore, a perfect correction cannot be made with a diffractive lens. Nevertheless, with a linear correction, the optical performance can be greatly improved.

10

When the eyemodel of Navarro (1985) is used, together with a 20 diopter silicone refractive intraocular lens instead of the natural lens, the chromatic aberration can be estimated by calculating the power of the eyemodel at different wavelengths. A graph similar to figure 1 will be the result. In order to determine how the diffractive lens must perform, a linear fit is made through the curve of the ideal correction. The result is:

15

$$P = -1.68 \cdot 10^7 \cdot \lambda + 69.6$$

$$P = \text{power [1/m]}$$

$$\lambda = \text{wavelength [m]}$$

20

This gives the ratio between the refractive and diffractive IOL power for a chromatic correction lens:

For the eyemodel with a refractive IOL:

$$CA = -\frac{\partial P}{\partial \lambda} = 1.68 \cdot 10^7$$

So:

$$\frac{2}{w^2} = -1.68 \cdot 10^7 \Rightarrow w = 0.345 \text{ mm} \Rightarrow P_d = \frac{2\lambda}{w^2} = 9.24 \text{ diopter}$$

25

(here,  $\lambda$  is the design wavelength of 550 nm)

$P_d$  = IOL diffractive power

Since the diffractive IOL power is 9.24 diopter, the refractive IOL power has to be reduced by the same amount. Reducing the refractive IOL power will reduce the chromatic aberration of the eyemodel also. In practice, equilibrium has to be found between the refractive and diffractive IOL power by an iterative design process,  
 5 where the diffractive IOL power will end up somewhere between 0 and 9.24 diopter.

*Description of the lens:*

The example lens is made of silicone material. Its shape is equi-biconvex. The anterior surface of the lens comprises an aspheric refractive lens, on which a  
 10 diffractive profile is superimposed. The diffractive profile takes care of 41% (8.25D) of the lens power, while the aspheric refractive lens does the remaining 59% (11.75D). The width of the first zone is 0.365 mm, and there are 67 rings needed to fill a full 6.0 mm IOL optic. In the periphery of the lens, the diffractive rings are 22 microns apart from each other.

15

The IOL is optimized for the Navarro (1985) eyemodel. The Navarro eyemodel has an aspheric cornea and includes dispersion for the ocular media. The surface information for the eye model and the lens is given in table 2. The lens designed is dependent on the eye model chosen. It must be noted that it is possible to design lenses using other  
 20 eye models of actual physiological data from patients.

\*LENS SURFACE DATA - Navarro 1985 with an IOL

Surface	Radius	Thickness	Aperture Radius	Glass	Special surface
Object	--	1.0000e+20	1.000e+14	AIR	
1	7.7200	0.5500	2.833 (solved)	CORNEA	Asphere
2	6.5000	3.050	2.778 (solved)	AQUEOUS	
3 (pupil)	--	--	2.500 (solved)	PUPIL	
4	--	0.900	2.500 (solved)	AQUEOUS	
5	20.994	1.125	2.418 (solved)	SILICONE	Asphere Diffractive
6	-20.994	18.157 (solved)	2.298 (solved)	VITREOUS	
Image	--	--	1.674e-05 (solved)	--	

25 CONIC AND POLYNOMIAL ASPHERIC DATA

Surface	conic constant	AD	AE
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1	-0.260000	--	--
5	-2.000000	-0.000459	-4.1000e-07

5

## \*DIFFRACTIVE SURFACE DATA (symmetric diffractive surface)

Surface	Diffraction order	Design $\lambda$	Kinoform construction order	Kinoform zone depth	DFO	DF1
5	1	0.550 $\mu\text{m}$	1	--	--	-0.004125

## 10 \*WAVELENGTHS

$\lambda$ number	Wavelength ( $\mu\text{m}$ )	Weight
1	0.5500	0.9950
2	0.4500	0.0380
3	0.6500	0.1070
4	0.5100	0.5030

## \*REFRACTIVE INDICES

Surface	Name	Index $\lambda(1)$	Index $\lambda(2)$	Index $\lambda(3)$	Index $\lambda(4)$	$v$
Object	AIR	1.000000	1.000000	1.000000	1.000000	--
1	CORNEA	1.377400	1.383500	1.374200	1.379328	40.580645
2	AQUEOUS	1.338800	1.345100	1.335600	1.340767	35.663158
3	PUPIL	1.338800	1.345100	1.335600	1.340767	35.663158
4	AQUEOUS	1.338800	1.345100	1.335600	1.340767	35.663158
5	SILICONE	1.459620	1.484950	1.454470	1.465680	15.079396
6	VITREOUS	1.337400	1.343400	1.334300	1.339286	37.076923
Image	IMAGE	--	--	--	--	--

## 15 Table 2

*Behavior of the lens:*

4 discrete wavelengths were used to evaluate the eyemodel including the refractive/diffractive IOL. The focus point is defined as the point where the

20 polychromatic MTF (Modulation Transfer Function) has it's maximum at 50 cycles/mm. The polychromatic MTF is determined by the weighed average of the 4



MTF's at the 4 wavelengths used. The weighting of the wavelengths was done using the standard luminance of the eye under photopic light conditions, which represents the relative sensitivity of the retina for different wavelengths.

The actual back focal length (ABFL) for the 4 different wavelengths indicates the presence of a chromatic difference in focus and by definition the amount of longitudinal chromatic aberration. The calculations are performed at a 5.0mm aperture in order to maximize the differences.. From these figures, shown in table 3, it can already be concluded that the spherical aberration is virtually eliminated, indicated by the close to diffraction limited performance. The IOL is optimized for chromatic aberration, but there is still some left, as already expected theoretically.

The figures in table 4, for a corresponding aspheric refractive design, without chromatic correction, show that indeed at each wavelength, the spherical aberration is well corrected with respect to the MTF(50) for the spherical refractive IOL and the MTF reaches the diffraction limit. The focal points of the different wavelengths do not work well together, so that the polychromatic MTF is lower than that found for the diffractive/refractive IOL.

Spherical lenses, which are now current practice, give much lower values. The figures corresponding to these lenses are shown in table 5.

Refractive/diffractive IOL			
$\lambda$	ABFL	MTF(50)	Diff limit
450	17.92	0.91	0.92
510	18.17	0.90	0.90
550	18.16	0.90	0.90
650	17.90	0.88	0.88
poly	18.16	0.82	0.90
[nm]	[mm]	[-]	[-]

Table 3

Aspherical refractive IOL			
$\lambda$	ABFL	MTF(50)	Diff limit
450	17.26	0.92	0.92
510	17.98	0.90	0.91
550	18.22	0.90	0.90
650	18.41	0.88	0.88
poly	18.22	0.56	0.90
[nm]	[mm]	[-]	[-]

Table 4

Spherical refractive IOL:			
$\lambda$	ABFL	MTF(50)	Diff. limit
450	17.13	0.30	0.92
510	17.84	0.30	0.91
550	18.06	0.31	0.90
650	18.15	0.32	0.88
poly	18.05	0.21	0.90
[nm]	[mm]	[-]	[-]

Table 5

The Polychromatic Modulation Transfer Functions for these three lenses are shown in Fig. 2, together with the diffraction limit.

## Example 2

### Background theory:

If a lens, which has fewer rings and thus also larger distances between the rings is preferred, for example for manufacturing reasons, a different step height for the diffractive profile could be used. A diffractive lens that is on the market, CeeOn™ 811E, Pharmacia has a 4D diffractive part, a zone width of 0.5mm and 32 rings.

A 8.25D diffractive lens with the same spacings between the rings as the existing 811E can be achieved by doubling the step height of the rings. With a double stepheight, the diffractive lens will have a phase jump of  $2\lambda$ , and therefore give its maximum efficiency in its 2<sup>nd</sup> order. For an 8.25D lens, the zone width will be 0.516mm while 33 rings will be needed for a 6mm optic. The minimum distance between the rings (periphery) is 45 microns.

The example lens is made of silicone material. Its shape is convex-plano. The anterior surface of the lens is aspheric. The flat posterior surface has a diffractive profile with a phase jump of two. The light distribution between the different diffractive orders is

given in figure 3. From this graph we see that only order 1 to 3 are relevant in the visible light range. We also see that there is some bifocal behavior at 475nm, but the eye is very insensitive to light at this wavelength (as indicated by the eye's spectral sensitivity, also shown in figure 3).

5

*Description of the lens:*

As in example 1, the diffractive profile takes care of 41% (8.25D) of the lens power, while the aspheric refractive lens does the remaining 59% (11.75D).

- 10 The IOL is optimized for the Navarro (1985) eyemodel. The Navarro eyemodel has an aspheric cornea and includes dispersion for the ocular media. The surface information for the eye model and the lens is given in table 6.

\*LENS DATA - Navarro 1985 with an IOL.

15

Surface	Radius	Thickness	Aperture Radius	Glass	Special surface
Object	--	1.0000e+20	1.000e+14	AIR	
1	7.7200	0.5500	2.833 (solved)	CORNEA	Asphere
2	6.5000	3.050	2.778 (solved)	AQUEOUS	
3 (pupil)	--	--	2.500 (solved)	PUPIL	
4	--	0.900	2.500 (solved)	AQUEOUS	
5	10.521	1.125	2.418 (solved)	SILICONE	Asphere
6	--	--	2.302 (solved)	AQUEOUS	Diffractive *2
7	-20.994	18.256	2.302 (solved)	VITREOUS	
image	--	--	0.001279 (solved)	--	

\*CONIC AND POLYNOMIAL ASPHERIC DATA

Surface	Conic constant	AD	AE
1	-0.260000	--	--
5	-4.900000	--	--

20

\*DIFFRACTIVE SURFACE DATA

Surface	Diffraction order	Design $\lambda$	Kinoform construction order	Kinoform zone depth	DFO	DF1
6	1	0.550 $\mu\text{m}$	1	--	--	-0.002063

## \*WAVELENGTHS

$\lambda$ number	Wavelength ( $\mu\text{m}$ )	Weight
1	0.5500	0.9950
2	0.4500	0.0380
3	0.6500	0.1070
4	0.5100	0.5030

5

## \*REFRACTIVE INDICES

Surface	Name	Index $\lambda(1)$	Index $\lambda(2)$	Index $\lambda(3)$	Index $\lambda(4)$	v
Object	AIR	1.000000	1.000000	1.000000	1.000000	--
1	CORNEA	1.377400	1.383500	1.374200	1.379328	40.580645
2	AQUEOUS	1.338800	1.345100	1.335600	1.340767	35.663158
3	PUPIIL	1.338800	1.345100	1.335600	1.340767	35.663158
4	AQUEOUS	1.338800	1.345100	1.335600	1.340767	35.663158
5	SILICONE	1.459620	1.484950	1.454470	1.465680	15.079396
6	AQUEOUS	1.338800	1.345100	1.335600	1.340767	35.663158
7	VITREOUS	1.337400	1.343400	1.334300	1.339286	37.076923
Image	IMAGE	--	--	--	--	--

Table 6

10 *Behavior of the lens:*

Using the same wavelengths as in example 1 and ignoring the changes in efficiency of the diffractive lens, the polychromatic modulation at 50c/mm is 0.81 (limit = 0.90), which is similar to the lens in example 1. If also the 1<sup>st</sup> and 3<sup>rd</sup> orders of the diffractive lens are included in the calculation, taking their corresponding efficiencies

15 into account, the polychromatic modulation at 50c/mm is 0.79.

The polychromatic MTF including 1<sup>st</sup> and 3<sup>rd</sup> order for the different lenses are shown in Fig. 4.

## Claims

- 5 1. An ophthalmic lens comprising a diffractive part, **characterized in that** it further comprises a refractive part comprising at least one surface, which is configured to compensate a passing wavefront at least partly for at least one type of monochromatic aberration introduced by at least one of the optical parts of the eye, said diffractive part being capable of compensating a passing wavefront at  
10 least partly for chromatic aberration introduced by at least one of the optical parts of the eye, said refractive and diffractive parts together contribute to a required power of the lens.
- 15 2. An ophthalmic lens according to claim 1, wherein the diffractive part also is capable of compensating a passing wavefront at least partly for chromatic aberration introduced by the refractive part of the lens.
- 20 3. An ophthalmic lens according to claim 1 or 2, wherein the refractive part also is capable of compensating a passing wavefront at least partly for at least one type of monochromatic aberration introduced by the diffractive part of the lens.
- 25 4. An ophthalmic lens according to any one of the preceding claims, wherein said lens is designed to compensate at least partly for values of monochromatic and chromatic aberrations measured in the eye of an individual patient.
5. An ophthalmic lens according to any one of the claims 1-3, wherein said lens is designed to compensate at least partly for an average value of monochromatic and/or chromatic aberration determined by measurements of a group of people.
- 30 6. An ophthalmic lens according to any one of the preceding claims, wherein said refractive part comprises at least one surface, which is configured to compensate a passing wavefront at least partly for spherical aberration introduced by at least one of the optical parts of the eye and optionally also by the diffractive part of the lens.

7. An ophthalmic lens according to any one of the preceding claims, wherein the refractive part comprises an aspheric surface, which compensates a passing wavefront at least partly for the spherical aberration introduced by at least one of the optical parts of the eye and optionally also by the diffractive part of the lens.
- 5
8. An ophthalmic lens according to claim 7, wherein said aspheric surface is capable of compensating at least partly for spherical aberration as expressed by the 11<sup>th</sup> normalized Zernike term.
- 10
9. An ophthalmic lens according to any one of the preceding claims, wherein the lens together with the eye provides a polychromatic image quality, which when expressed as MTF(50) (Modulation Transfer Function at 50 cycles per millimeter) performs at least about 40% higher than an aspheric lens compensating for the same spherical aberration as the inventive lens but without compensating for the chromatic aberration.
- 15
10. An ophthalmic lens according to any one of the preceding claims, wherein the diffractive part is a diffractive surface profile.
- 20
11. An ophthalmic lens according to claim 10, wherein the diffractive surface profile consists of a number of concentric rings.
- 25
12. An ophthalmic lens according to claim 11, wherein the profile height of the diffractive surface profile equals an integer number of the design wavelength.
13. An ophthalmic lens according to claim 11, wherein the profile height of the diffractive surface profile is one design wavelength.
- 30
14. An ophthalmic lens according to any one of the preceding claims, wherein the anterior surface is an aspheric surface, on which a diffractive profile is superimposed.
15. An ophthalmic lens according to claim 13 and 14, wherein the radial width of the first zone of the diffractive profile is 0.365 mm for a 20D lens.

16. An ophthalmic lens according to claim 11, wherein the profile height of the diffractive surface profile is two design wavelengths.
- 5 17. An ophthalmic lens according to any one of the preceding claims except claim 14, wherein the anterior surface of the lens is an aspheric surface and the posterior surface of the lens is flat and has a diffractive profile.
- 10 18. An ophthalmic lens according to claim 16 and 17, wherein the radial width of the first zone of the diffractive profile is 0.516 mm for a 20D lens.
19. An ophthalmic lens according to any one of the preceding claims except claim 17, wherein the shape of the lens is equi-biconvex.
- 15 20. An ophthalmic lens according to any one of the claims 1-18, wherein the shape of the lens is convex-plano.
21. An ophthalmic lens according to any one of the preceding claims, wherein the lens material is a silicon.
- 20 22. An ophthalmic lens according to any one of the preceding claims, wherein the lens material is PMMA or an hydrogel.
23. A method for designing an ophthalmic lens according to any one of the claims 1-22, comprising:
- 25 - combining a refractive part and a diffractive part of the lens such that they together compensate a passing wavefront at least partly for at least one type of monochromatic aberration and for chromatic aberration introduced by at least one of the optical parts of the eye, while dimensioning said refractive and diffractive
- 30 parts to provide the lens with a required power.
24. A method according to claim 23, further comprising the steps of:
- measuring at least one type of monochromatic aberration provided to a wavefront from at least one of the optical parts of an eye; and

- combining the refractive and diffractive parts of the lens such that they compensate at least partly for the measured monochromatic aberration.

25. A method for designing an ophthalmic lens according to claim 23 or 24, further  
5 comprising the steps of:
- measuring the spherical aberration provided to a wavefront from at least one of the optical parts of an eye;
  - combining the refractive part and the diffractive part of the lens such that they together compensate a passing wavefront at least partly for the measured spherical  
10 aberration introduced by at least one of the optical parts of the eye.
26. A method according to any one of the claims 23-25, comprising measuring the chromatic aberration provided to a wavefront from at least one of the optical parts of the eye and combining the refractive and diffractive parts of the lens such that  
15 they together compensate a passing wavefront at least partly for the measured chromatic aberration introduced by at least one of the optical parts of the eye.
27. A method according to any one of the claims 23-25, comprising combining the refractive and diffractive part of the lens such that they together compensate a  
20 passing wavefront at least partly for an average chromatic aberration of human eyes in general or of eyes in a specific group of people. ....
28. A method according to claim 23, comprising combining the refractive and the diffractive part of the lens such that they together compensate a passing wavefront  
25 at least partly for an average monochromatic aberration of eyes in general or of eyes in a specific group of people. .
29. A method according to any one of the claims 23-28, comprising combining the refractive and diffractive part of the lens such that the diffractive part compensates  
30 a passing wavefront at least partly for the chromatic aberration introduced by the refractive part of the lens.
30. A method according to any one of the claims 23-29, comprising combining the refractive and the diffractive part of the lens such that the refractive part



compensates a passing wavefront at least partly for the monochromatic aberration introduced by the diffractive part of the lens.

- 5 31. A method according to any one of the claims 23-30, comprising measuring the refractive error of the eye and dimensioning the refractive and diffractive parts of the lens such that they together compensate at least partly for the refractive error of the eye.
- 10 32. A method according to any one of the claims 23-31, comprising providing the refractive part with an aspheric surface, which compensates a passing wavefront at least partly for the spherical aberration introduced by at least one of the optical parts of the eye and optionally also by the diffractive part of the lens.
- 15 33. A method according to any one of the claims 23-32, comprising providing the refractive part with an aspheric surface, which is adapted to compensate at least partly for spherical aberration as expressed by the 11<sup>th</sup> normalized Zernike term.
- 20 34. A method according to any one of the claims 23-33, comprising providing the lens with a diffractive surface profile.
35. A method according to claim 34, comprising providing the diffractive surface profile with a number of concentric rings.
- 25 36. A method according to claim 35, comprising providing the diffractive surface profile with a profile height that equals an integer number of the design wavelength.
- 30 37. A method according to any one of the claims 23-36, comprising providing the anterior surface of the lens with an aspheric refractive lens and superimposing a diffractive profile on top of it.
38. A method of designing an ophthalmic lens according to any one of the claims 1-22, characterised by the steps of:

- i) selecting an eye model with a refractive aspheric ophthalmic lens of a predetermined refractive power and a predetermined amount of at least one monochromatic aberration;
- ii) estimating the power of said eye model at different wavelengths, so as to determine the chromatic aberration of the eye model;
- iii) estimating a correction function of how the power varies with the wavelength to be an ideal compensation for said chromatic aberration of the eye model;
- iv) finding a linear function of how power varies with the wavelength, which suitably approximates said correction function;
- v) calculating a provisional zone width of a diffractive profile corresponding to this linear function and also calculating the diffractive power of this diffractive profile;
- vi) reducing the refractive power of the refractive ophthalmic lens by the amount of power calculated for the diffractive profile;
- vii) estimating a new correction function of step iii), finding a new linear function of step iv) and calculating a new provisional zone width and a new diffractive power for a new diffractive profile corresponding to this new linear function;
- viii) adjusting the refractive power of the refractive ophthalmic lens such that the total power of a hybrid lens, which comprises both the refractive ophthalmic lens and the diffractive profile and which is adapted to replace the refractive ophthalmic lens in the eye model, equals the predetermined power;
- ix) repeating steps vii) to viii) until a suitable combination of a refractive and a diffractive part of the hybrid ophthalmic lens is found that both provide the eye model with a predetermined power and with a suitable reduction in chromatic aberration.

39. A method according to claim 38, further comprising as a last step measuring the monochromatic aberration of the combination of the eye and the hybrid ophthalmic lens of claim 38 and correcting the refractive part of the ophthalmic lens according to the measurements such that the monochromatic aberration is reduced sufficiently for the combination of eye and ophthalmic lens.

40. A method according to claim 38 or 39, wherein the at least one monochromatic aberration of the refractive ophthalmic lens is spherical aberration.

41. A method according to any one of the claims 38-40, wherein the eye model used is the eye model of Navarro (1985).
- 5 42. A method according to any one of the claims 38-41, wherein the profile height of the diffractive profile equals an integer number of the design wavelength.

1/2

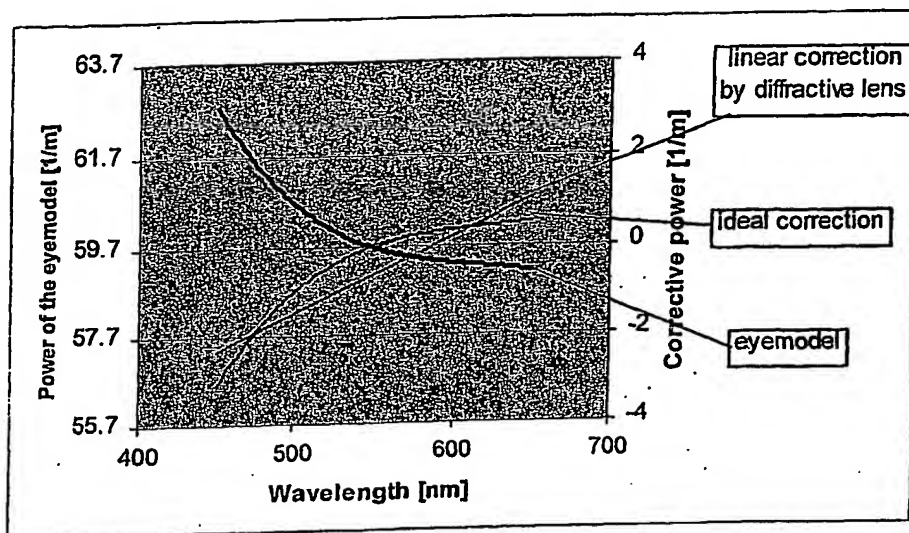


Fig. 1

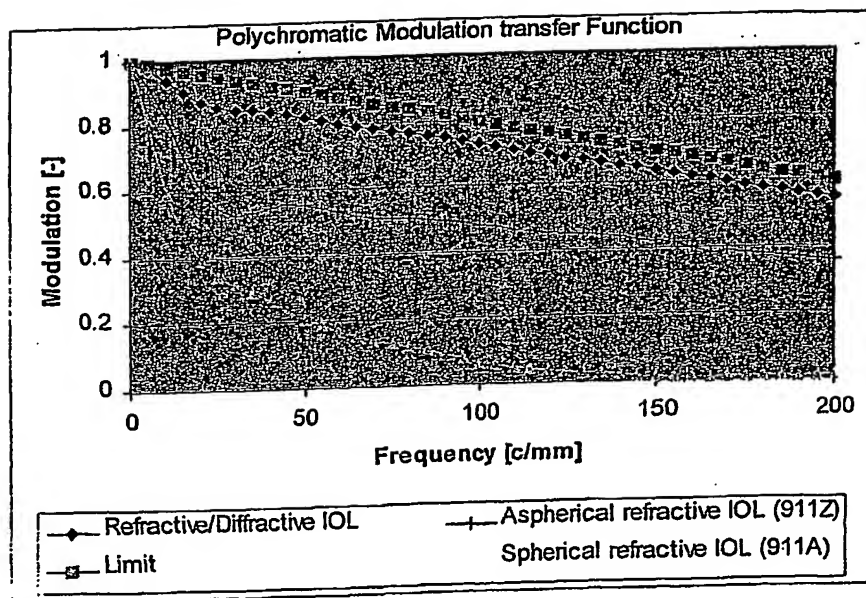


Fig. 2

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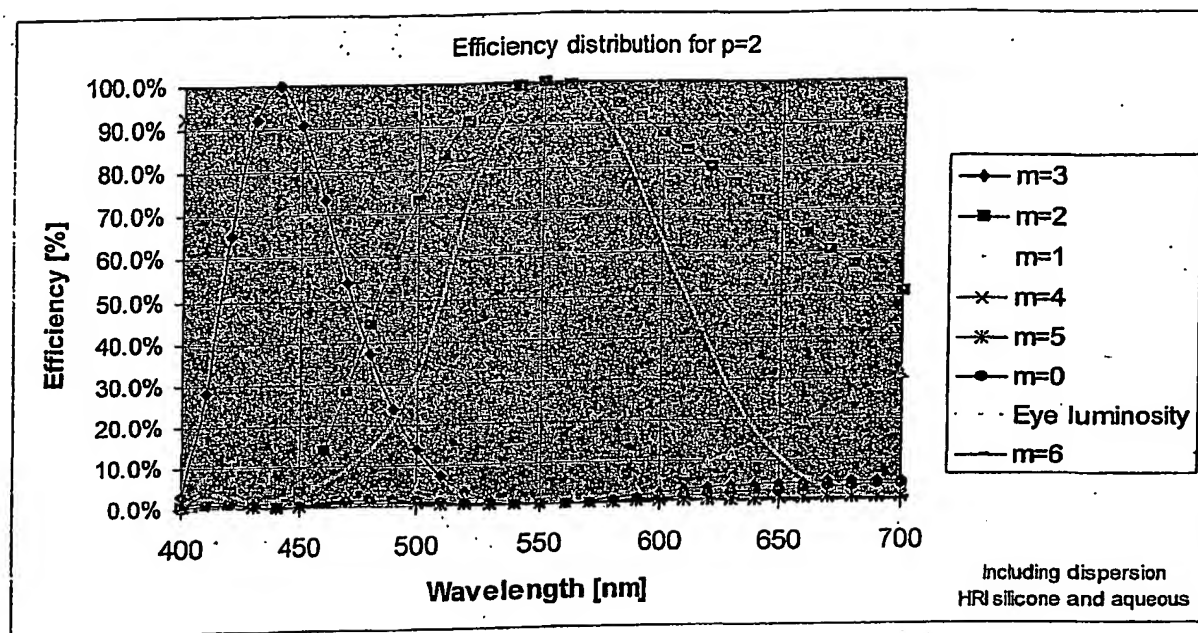


Fig. 3

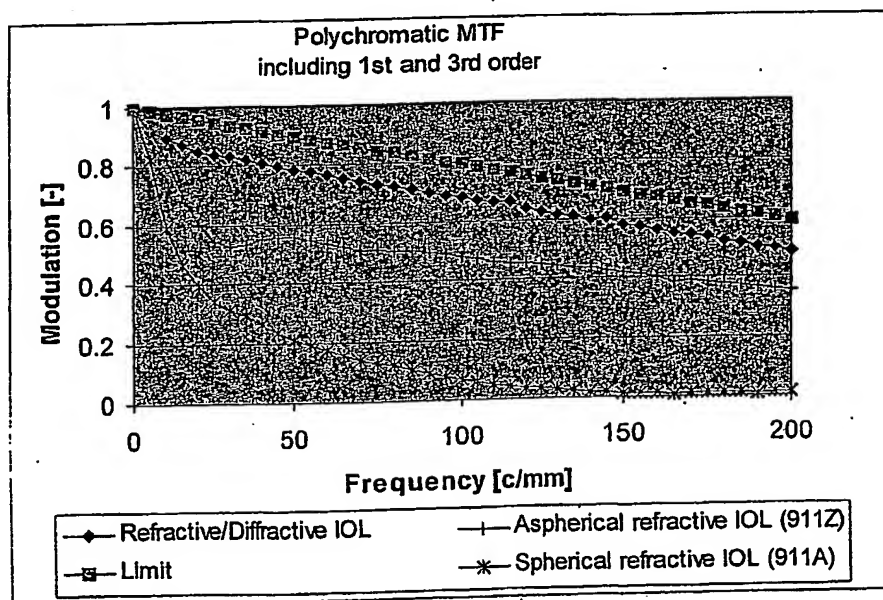


Fig. 4